Jupiter Icy Moons Orbiter
Mission Design Overview

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Condensed Abstract

An overview of the design of a mission to three large moons of Jupiter (Callisto, Ganymede, and Europa) is presented. The Jupiter Icy Moons Orbiter (JIMO) mission uses ion thrusters powered by a nuclear reactor to transfer from Earth to Jupiter and enter a low-altitude science orbit around each of the moons. The combination of very limited control authority and significant multibody dynamics resulted in some aspects of the trajectory design being different than for any previous mission. The results of several key trades, innovative trajectory types and design processes, and remaining issues are presented.

Extended Abstract

A challenging aspect for low-thrust mission design in general is that the trajectory design is closely coupled with other project elements, even at an early stage. The trajectory depends on the launch vehicle capability, the mass of the spaceship, characteristics of the power and propulsion subsystems, and capabilities of the attitude control. With JIMO being the first Prometheus mission, this coupling proved even more challenging since the system parameters had large uncertainties initially and significant external constraints as the design progressed.

An extensive database of direct interplanetary trajectories was created in order to be able to quickly perform broad trades in system parameters such as power, specific impulse (I_{sp}), and mass. When coupled with subsystem mass models and potential launch vehicle capabilities, the database was used to explore a large trade space constrained by technological and other practical considerations. We could then focus on regions with reasonable system parameters and good mission characteristics.

Several options were considered for departure from Earth. The most appropriate option depends on the capabilities of the launch vehicles being considered. One option is to launch into an orbit about the Earth and use electric propulsion to gain energy and escape the Earth. Another option is to use the launch vehicle or a chemical transfer stage to escape the Earth. Spiraling out with electric propulsion provides more delivered mass or requires less launch vehicle capability but typically has a longer flight time. The project decided early on to escape the Earth using a chemical propulsion system. The Level 1 requirement on arrival date forced a flight time that would have been difficult to meet with a spiral out option.

The reference interplanetary trajectory is a direct trajectory with no planetary gravity assists (Figure 1). We performed an extensive analysis of a variety of gravity assist options with Earth, Venus, and Mars. Results of one of these analyses are shown in Figure 2. The solid black line in Figure 2 is the direct case with optimized launch energy. All the other cases include at least one planetary gravity assist. There are many gravity assist options that both increase the delivered mass and decrease the flight time. Some of the Earth gravity assist options are particularly interesting because they are among the best performers and provide consistent performance at regular intervals of launch opportunities.

The injection period for the reference trajectory can be quite long without sacrificing significant performance. For example, the injection period is potentially as long as 84 days at the cost of 0.3% of delivered mass to Jupiter. If we were to allow slightly longer transfer times for backup injection opportunities, the injection period could be extended indefinitely at a reasonable cost in performance. The mission is also extremely robust to injection vehicle delivery dispersions.

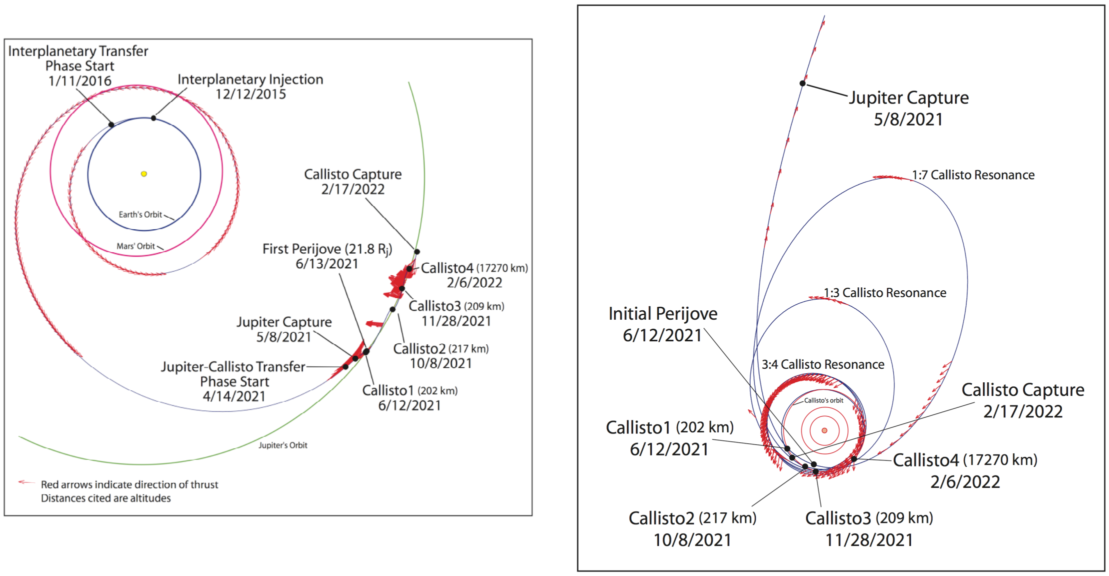

Figure 1 Reference Interplanetary Trajectory and Jupiter Arrival

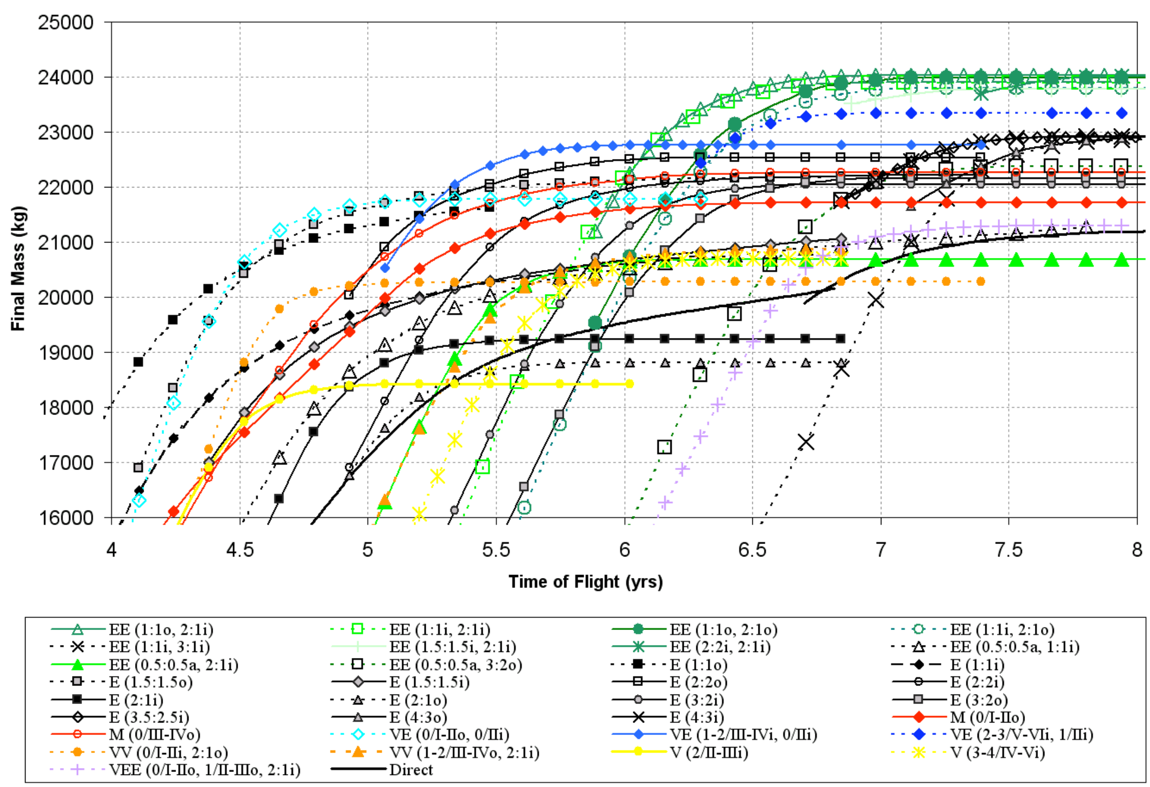

Figure 2 Gravity Assist Trajectories

The reference trajectory flies by Callisto on the initial approach to Jupiter and uses additional Callisto gravity assists prior to capture at Callisto (Figure 1). These gravity assists reduce the required propellant for this phase of the mission by about 80% and also decrease the flight time. We analyzed using Ganymede for gravity assists prior to capture at Callisto, but the results showed that Ganymede did not help when Callisto was to be the first moon orbited.

The reference trajectory orbits Callisto, Ganymede, and Europa, in that order. We also analyzed orbiting Europa first, then Ganymede, then Callisto. The delivered mass performance was very similar between the two cases. The Callisto first case has a slightly shorter flight time and lower radiation – potentially much lower radiation depending on the end-of-mission orbit.

The dynamical environment at Jupiter is complex. The trajectories at Jupiter are governed by multiple gravitational fields and spend considerable time in regions of space in which more than one body is exhibiting significant influence on the spaceship. With appropriate design techniques, we can find very efficient pathways by taking advantage of these intricate dynamics. An additional complexity results from the very low acceleration capability of the spaceship. We are virtually being churned around by the ocean while using an oar for control. We must choose our strokes carefully and deliberately. The combination of very limited control authority and significant multibody dynamics results in some aspects of the trajectory design being different than for any previous mission.

Capturing at a body using low-thrust propulsion is different than for high-thrust missions. The reduction in orbital energy is necessarily slower; hence, a substantial amount of time is spent in a transition region between escaped from the moon and captured at the moon. During this transition, the multibody effects are significant, and in many cases an uncontrolled spaceship would impact in a matter of days (Figures 3 and 4). This was particularly true when we tried to capture directly into near-polar inclination orbits. We did find very stable near-equatorial, retrograde orbits that we could capture into, but to avoid the unstable regions, we had to change the inclination at relatively low altitudes which is very costly in terms of propellant and flight time. At Callisto and Ganymede, we could follow paths to the science orbit that would not impact for at least a couple weeks; however, this is extremely costly at Ganymede since the relatively safe region is at a much lower altitude with Ganymede being closer to Jupiter. At Europa, the relatively safe region essentially disappears within about 45 deg of the poles. With the extremely high radiation environment at Europa, the decision was made to get to the science orbit as fast as reasonably possible, allowing the uncontrolled lifetime to be very short.

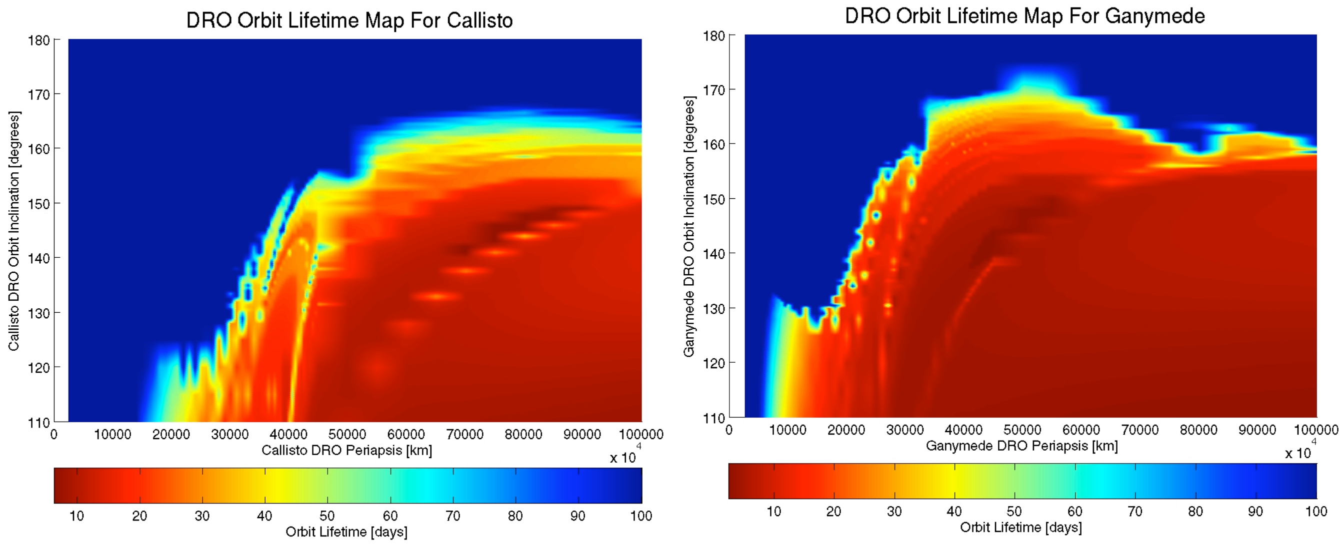

Figure 3 Orbit Lifetime Maps for Ganymede and Callisto

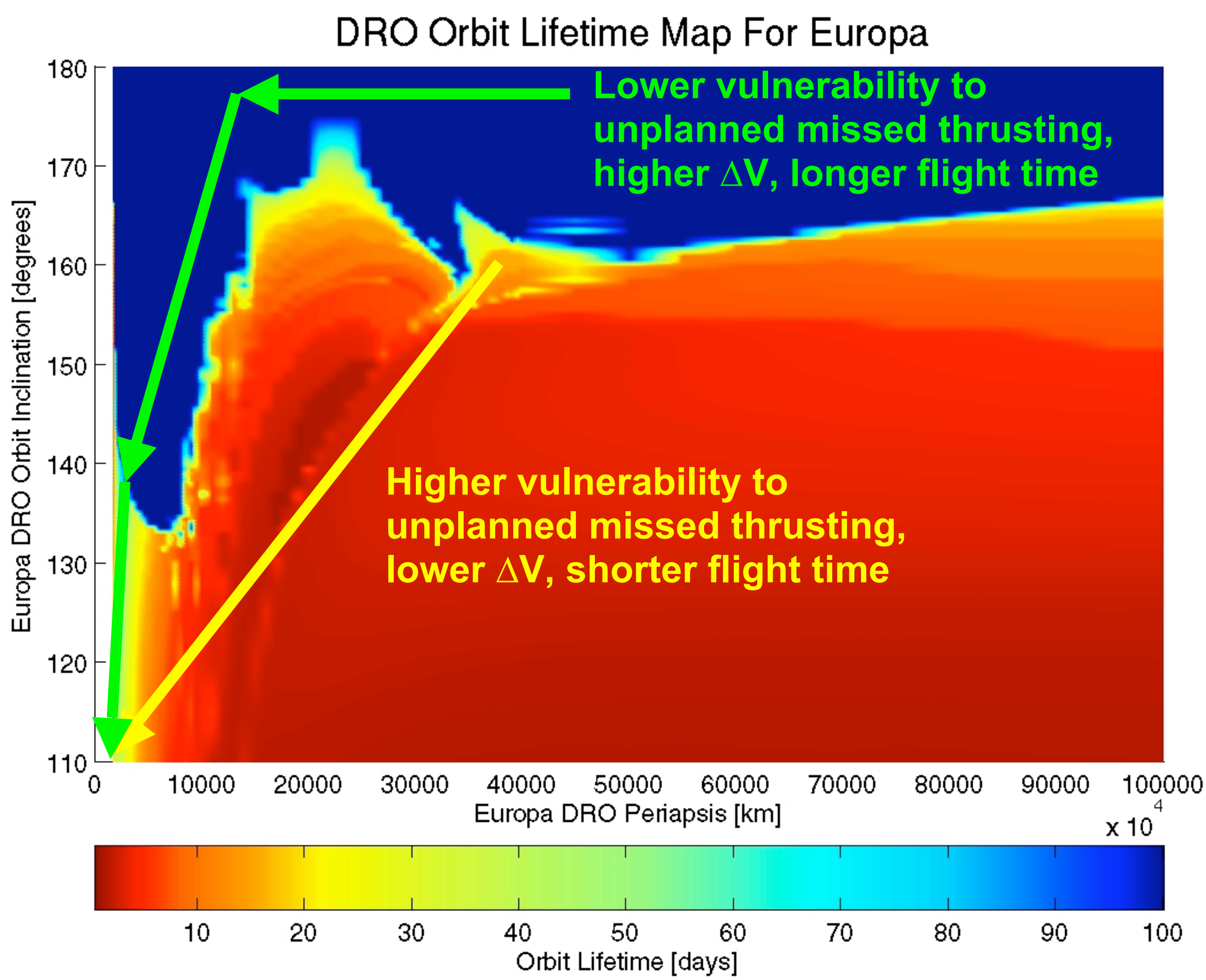

Figure 4 Orbit Lifetime Map for Europa

We recently began exploring and discovering other types of captures that are very promising. These “manifold captures,” as we referred to them, approach the moons along stable manifolds of unstable periodic orbits (of which there are many) near the moons. The manifold captures performed well in terms of propellant mass, flight time, and controllability with reasonable lifetimes. These types of captures would have been explored more fully given more time. They may also be very useful for high-thrust missions.

Overall, significant trades are available between propellant mass, flight time, and stability for a variety of capture types. The requirements on trajectory lifetimes and acceleration levels (translational and rotational) will drive the design of the captures and, hence, many other aspects of the mission.

Figure 5 illustrates the capture at Callisto and transfer down to the science orbit.

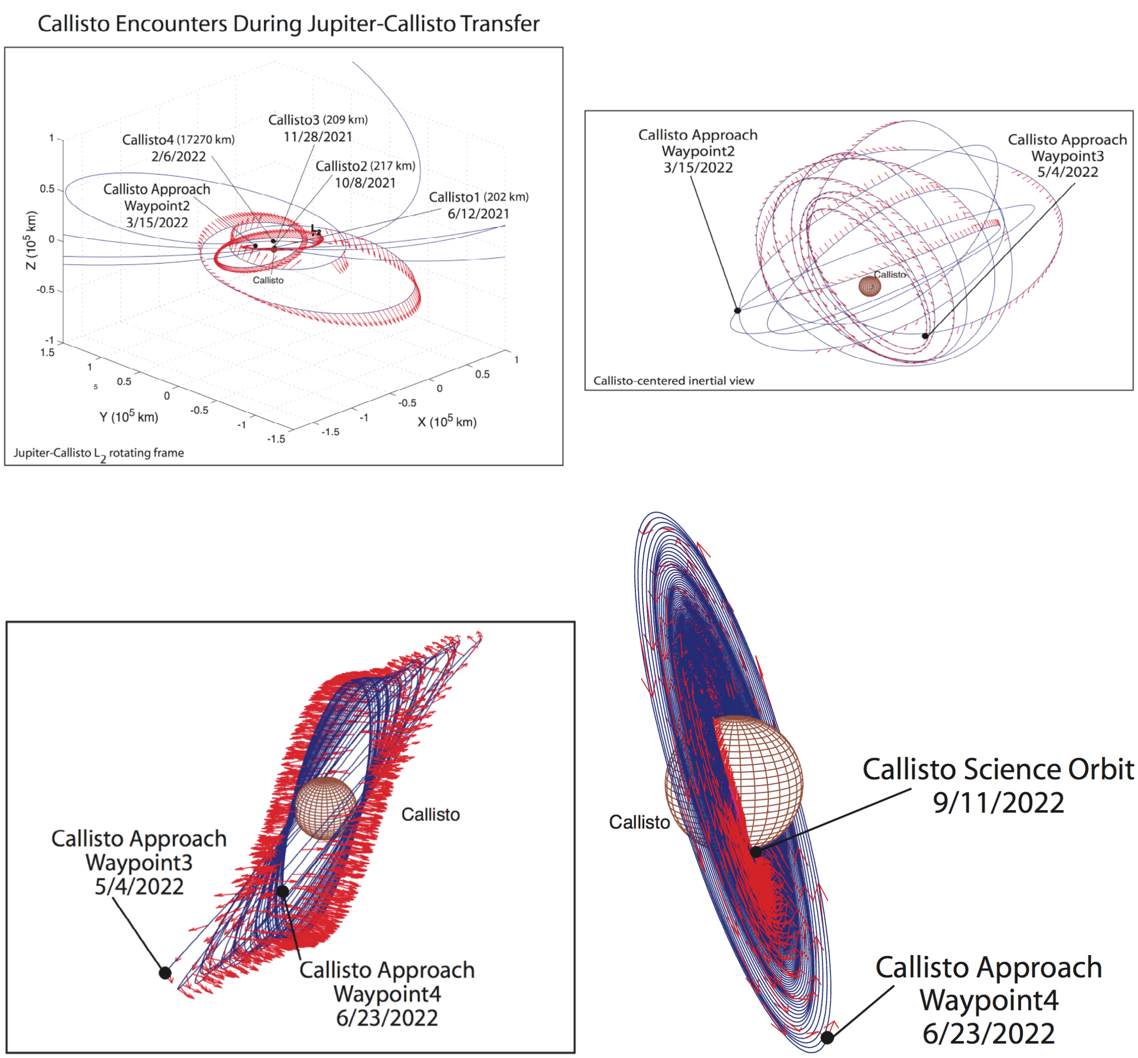

Figure 5 Capture at Callisto and Transfer to the Science Orbit

We knew from previous studies that low-altitude orbits around the moons with inclinations within about 45 deg of the poles are unstable due to the gravitational influence of Jupiter, that is, if left uncontrolled, they impact the moon in a relatively short time. Since Europa is the closest to Jupiter of the icy moons and also the smallest, the time scale for this effect is the shortest at Europa with impact occurring on the order of 10s of days. The previous studies considered only a very simple gravity field for the moons, including only the effect of J2. When we started considering more detailed gravity fields, we discovered that higher order terms can have a significant effect on the stability of the orbits. For example, a significant value for J3 makes orbits at essentially all inclinations unstable. We did discover very special cases of near polar "frozen orbits" that have relatively long lifetimes, but the exact orbital conditions for these orbits depend on the details of the gravity field which we won't know until we have been at the moon for awhile.

Stability of the orbits also has a direct effect on the science orbit maintenance and, hence, the orbit determination. A trade exists between the frequency and total delta-V required for the maintenance maneuvers, with smaller, more frequent maneuvers potentially resulting in less ΔV overall. Lower total ΔV results in less total time interruption to the science, but the more frequent maneuvers may significantly degrade the orbit determination. So the selection of the precise elements for the science orbits and the orbit maintenance strategy are still unclear.

The transfers between the moons take advantage of multibody effects and gravity assists to reduce the required propellant for these phases of the mission by about 80%. We explored many different types of transfers, including various combinations of resonances with the moons. The best transfers depend on the type of escapes and captures used at the moons and the available level of acceleration. The transfer from Callisto to Ganymede for the reference trajectory is shown in Figure 6.

The mission ends with the spaceship in the science orbit at Europa. We explored options for transferring to orbits that do not impact Europa for an extended duration (> 1000 years), but the transfers require more propellant and more time in the high radiation environment at Jupiter.

The most recent reference trajectory satisfies all of the applicable Level 1 requirements. The delivered mass includes a Payload Accommodation Envelope with a mass capability of at least 1500 kg. Jupiter Orbit Insertion occurs on May 8, 2021, which is 5.4 years after injection. Science orbits are maintained around Callisto for 120 days, Ganymede for 120 days, and Europa for 60 days.

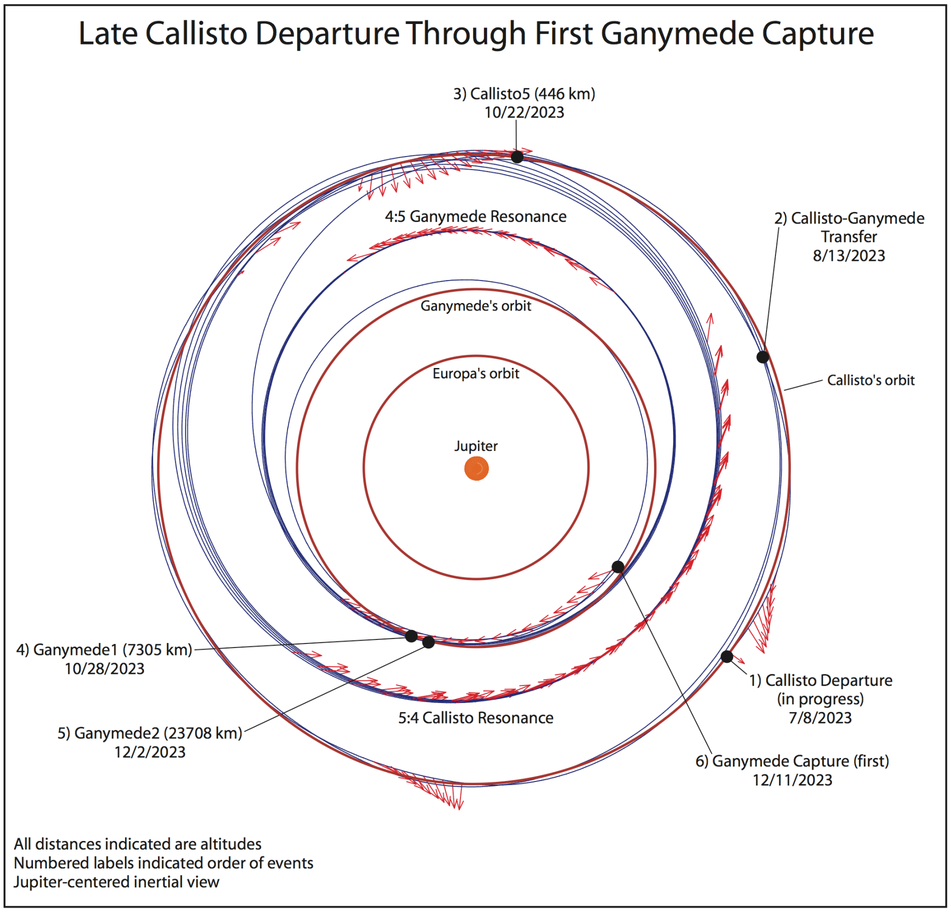

Figure 6 Transfer from Callisto to Ganymede

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